SOFT SWITCHING HIGH EFFICIENCY FLYBACK CONVERTER

Cross Reference to Related Applications

Priority is claimed from U.S. provisional patent application Serial No. 60/372,132 entitled "Soft Switching High Efficiency Flyback Converter" filed April 12, 2002 in the name of Ionel D. Jitaru. That application is incorporated herein by reference.

Field of the Invention

This invention relates to DC-DC converters and more particularly to a driving/synchronization technique used to achieve zero voltage switching and regulate the output of DC-DC converters.

Background of the Invention

In order to miniaturize power supplies, the control for power supplies should be simplified. Switching frequencies have been increased to reduce capacitive and magnetic elements in miniaturized power supplies. Still, in today's and future power supplies there is a need to reduce the number of components needed to control the power supply. Among the greatest challenges is communication across the isolation boundary. Several techniques exist. These include opto-couplers, transformers, radio frequency devices, etc. This invention provides a method and circuit that use the same transformer that is used for power conversion, i.e. the power transformer. The technique of this invention is not to send complicated encoded information, but to actually change the supply's effective duty cycle from the secondary.

A preferred embodiment of this invention is a self-oscillating flyback converter. The method and circuitry of the invention can be used with other topologies as well. The flyback converter is believed the best topology to illustrate the invention and the most easily understood. Plus, this topology offers a reduced number of control parts, which illustrates the advantage of this invention and makes it a preferred embodiment.

Fig. 2A shows a typical self-oscillating flyback converter in which an input voltage source 16 supplies a primary winding 18 of a transformer 32 in series with a

primary switch 8. Its turn OFF command is controlled by a combination of a transistor 22 and positive feedback from a winding 20, a capacitor 14 and a gate resistor 12. Turn ON is primarily controlled with the same winding circuit, plus a resistor 10 provides turn ON at initial startup. The transistor 22 is turned ON if the current through a resistor 24 is sufficiently high when the switch 8 is ON. During the times the switch 8 is OFF, it provides a voltage 25 alternating in polarity to the output circuit. When the output load circuit comprising a load 31 and a filtering capacitor 30 is coupled, during the OFF time of the switching period, current flows through secondary winding 26 of the transformer 32 and through a diode D1 to the output load 31 and the filter capacitor 30.

Fig. 2B displays certain voltage and current versus time waveforms for the self-oscillating flyback circuit parameters, i.e.: primary gate voltage 34 of the switch 8, primary drain voltage 36 of the switch 8, and the currents-transformer primary winding current 40 and the secondary winding current 38.

A first, main drawback of this approach is that there is no regulation. The control is simple, but adding regulation would ordinarily add complexity and parts. Plus, in the past, to regulate the output well, an opto-coupler was added. A second drawback is that for low output voltages the diode has a relatively large forward voltage drop. A third drawback is the primary switch 8 does not have zero voltage switching in all situations. By adding a synchronous rectifier in place of the diode D1, to serve as a switch in the secondary circuit, the second drawback can be avoided. However, this could introduce other problems including cross-conduction between the primary switch 8 and the synchronous rectifier which needs to be avoided.

There remains, therefore, a need for an approach to using primary and secondary switches in a converter such that self regulation is accomplished, the switch in the output secondary circuit exhibits a low forward voltage drop, zero voltage switching is accomplished and cross-conduction is avoided.

Summary of the Invention

In accordance with this invention, a method and circuit are employed in which energy is pushed back to the input or primary circuit from the secondary in a power conversion circuit to vary the circuit's duty cycle and in this way regulate the circuit's

output voltage. In a sense, the secondary changes the effective duty cycle by making the OFF time longer. This regulates the output. In the primary circuit, the extra energy that is pushed back is put to good use by providing zero voltage switching. This also prevents cross-conduction between the primary switch and the secondary's synchronous rectifier. Since zero volt switching can prevent switching losses at higher frequencies, higher frequencies can be employed to further reduce the size of the converter.

Controlling the timing of the secondary and primary MOSFETs serving as the synchronous rectifier and the primary switch is an important feature of this invention. The invention provides a simple method of achieving this and a general methodology.

It is an object of the present invention to provide a general concept of a flyback converter that is bi-directional. In other words, each of the two circuits coupled by the power transformer may be either the input, primary circuit or the output, secondary circuit. In the converter according to the present invention, by controlling MOSFET ON and OFF times correctly, zero voltage switching is accomplished for both MOSFETs. The algorithm according to which the converter operates to accomplish this is described below.

Objects of this invention are, among others:

1. A driving technique or concept (called herein the "algorithm") that accomplishes zero voltage switching in both the primary and secondary switching devices of a converter.

2. A regulation technique using the algorithm in the primary, secondary or both.

3. Circuits and methods of operation that implement detection and regulation of the driving technique by using one or more of winding voltage detection, current detection, or ripple detection in the secondary side of a DC-DC converter.

In accordance with one preferred embodiment of the invention, a DC to DC converter is provided that has first and second circuits including first and second semiconductor switches coupled with first and second windings of a power transformer and a control circuit coupled to each of the first and second circuits to control conduction in the semiconductor switches, at least one of the first and second control circuits sensing the direction of current through the associated semiconductor switch and turning ON that switch when a reverse current is detected. Preferably in the

preferred exemplary embodiment the control circuit that turns on the semiconductor switch upon the detection of reverse current turns that switch ON at a time when there is no voltage across the associated power transformer winding so as to provide substantially zero voltage switching.

In accordance with one preferred embodiment, both of the first and second control circuits that control the first and second semiconductor switches enable the switches to be turned ON when a reverse current through the switch is detected. In the preferred embodiments according to this invention, the DC-DC converter has at least one of the control circuits adapted to turn OFF the semiconductor switch controlled thereby in response to at least one operating parameter of the converter. Those operating parameters may be one or more of output voltage of the converter, voltage across one of the first and second windings or current in one of the semiconductor switches. In one preferred converter, it is the control circuit coupled to the first circuit in controlling relation to the first semiconductor switch that turns OFF that semiconductor switch as a function of the sensed converter operating parameter. In another preferred embodiment it is the second control circuit that controls the second semiconductor switch that turns OFF that semiconductor switch in response to the operating parameter and in yet a third embodiment both semiconductor switches are turned OFF based on converter operating parameters.

In another preferred embodiment of the invention it is a control winding on the power transformer that is coupled to the control circuit controlling one of the semiconductor switches. Preferably, in accordance with this invention in a number of preferred embodiments thereof, the first and second circuits coupled to the first and second windings can be either primary or secondary windings. Put another way, the DC-DC converter is bi-directional, moving power in either direction depending upon the control of the semiconductor switches.

An embodiment of this invention is a self-regulating DC-DC converter that has a secondary circuit voltage sensing control circuit connected to control the second semiconductor switch in dependence on a voltage related to converter output voltage. The secondary winding of this converter is coupled to conduct in a forward direction through the secondary switch a diminishing current in a forward direction upon termination of current in the power transformer's primary winding. The secondary

circuit voltage sensing control circuit is responsive to the voltage sensed to turn the secondary switch OFF when current in the secondary winding is in a range from substantially zero current to a level of reverse current, thereby inducing in the primary winding a current level in the range from about zero current to a reverse current level there. This then causes energy to be transferred back to the primary winding when the secondary circuit voltage sensing control circuit senses an over-voltage.

In one specific preferred embodiment, the secondary circuit voltage sensing control circuit employs a comparator having a reference voltage source connected to one input, the sensed voltage related to converter output voltage connected to another of the inputs and a control electrode of the secondary semiconductor switch coupled in switch controlling relation to an output of the comparator. In the preferred embodiment of this self-regulating DC-DC converter, the voltage that is related to converter output voltage is the voltage across the secondary winding of the converter's power transformer. In the self-regulating DC-DC converter, transfer of energy back to the primary for the purpose of self-regulation is accomplished by decreasing the duty cycle of the converter by altering the switching times of the secondary conductor switch when an over-voltage in the secondary circuit is detected.

Broadly, the preferred DC-DC converter embodiment of this invention can be described as a first control circuit coupled to a first circuit in controlling relation to a first semiconductor switch in current conduction relation to the first winding of a power transformer, a second control circuit coupled to a second circuit in controlling relation to a second semiconductor switch connected in current conducting relation to a second winding of the power transformer and sensing elements connected with each of the first and second control circuits to detect one or more operating parameters of the first and second circuits and enable the semiconductor switches to be turned ON in response thereto. Preferably the sensing element can be a control winding on the power transformer, elements responsive to current direction in the semiconductor switches, elements responsive to the level of current in the semiconductor switches, voltages across the first winding or the second winding, input voltage to the converter and output voltage from the converter and time delay. In all of the above-described preferred embodiments, the semiconductor switches may be MOSFETs. The MOSFET has an intrinsic turn-ON threshold which in one preferred embodiment can be, with the number

of turns in the control winding, used to control the turn ON of the second semiconductor switch. In a preferred embodiment, each MOSFET is turned on at zero drain voltage and with reverse current through the switch. The turn OFF times of the first and second semiconductor switches determines the direction of power flow through the converter.

Broadly, the method or technique according to a preferred approach to this invention following the algorithm for operating a DC-DC converter comprises providing the circuitry including a power transformer with first and second semiconductor switches in current conducting relation with first and second windings of the power transformer, applying the input DC voltage to a first circuit coupled to the first of the pair of windings, turning OFF the first semiconductor switch to induce a reverse current in the second winding and through the semiconductor switch in current conducting relation therewith, turning ON the second semiconductor switch connected with the second winding when voltage across the second winding is substantially zero and while current in the second winding and second semiconductor switches is reverse current, turning OFF the second semiconductor switch when current in the second winding and second semiconductor switch is forward current, turning ON the first semiconductor switch connected with the first winding when voltage across the first winding is substantially zero and while current in the first winding and the first semiconductor switch is reverse current. Preferably the method further includes sensing first and second currents in the first and second semiconductor switches and inputting first and second current detection signals to the first and second control circuits controlling the switches.

The above and further objects and advantages of the invention will be better understood from the following detailed description of at least one preferred embodiment of the invention, taken in consideration with the accompanying drawings.

Brief Description of the Drawings

Fig. 1A is a semi-generalized schematic of a self-oscillating flyback converter according to this invention;

Fig. 1B is a graphical illustration that plots selected waveforms of the converter according to Fig. 1A;

Fig. 2A is a schematic of a prior art self-oscillating flyback converter;

Fig. 2B is a graphical illustration that plots selected waveforms of a typical self-oscillating flyback converter such as that shown in Fig. 2A;

Fig. 3 is a schematic of a further embodiment of a flyback converter according to the invention;

Fig. 4A is a schematic partially in block diagram form of a generalized flyback converter according to the invention; and

Fig. 4B is a graphical illustration that plots selected waveforms of the generalized flyback converter of Fig. 4A.

Detailed Description

A semi-general illustration of the proposed concept applied to a self-oscillating flyback converter is illustrated in Fig. 1A with corresponding waveforms shown in Fig. 1B. Assume the converter is just powered up by applying an input voltage Vi from a DC voltage source 56. A resistor 52 charges a capacitor 57 and, through resistor 58, a gate capacitance of a MOSFET M1 acting as a primary switch 62. The MOSFET M1 turns ON when its gate threshold is reached. Voltage is applied to the primary winding 66 as the primary drain voltage 84 of M1 starts to go down at point T_0 as illustrated in Fig. 1B. This in turn produces a voltage on winding a 64 which increases the primary gate voltage 82 on the MOSFET M1 further. This saturates the device. This is shown at point 83 in Fig. 1B. Primary current 86 ramps up at a rate dependent on the inductance of the primary winding 66. When the primary current 86 reaches a level, at point 85 in Fig. 1B, that produces a drop across a resistor 65 larger than a V_{be} needed to turn ON a transistor 60, this transistor turns ON. This starts the discharge of the primary gate voltage 82 of the MOSFET M1 at a time T_1 shown in Fig. 1B. When the MOSFET M1 starts to turn off, the primary drain voltage 84 of the MOSFET M1 starts to rise. This changes the voltage on the positive feedback winding 64 to a lower value, which further shots OFF the MOSFET M1, more quickly producing a fast turn OFF of that switch. Once the MOSFET M1 is completely OFF the current built up in the primary winding 66 and transformer 67 must flow through an available winding, i.e. secondary winding 68. Put another way, collapse of the field built up by the current in the primary winding

66 causes the buildup of current in the secondary winding 68 as is typical in flyback converters. When the voltage on secondary winding 68 exceeds the output voltage V_0, the secondary current 88 starts to flow through the body diode 69 of a MOSFET M2.

A control circuit 75 for the MOSFET M2 is made up of a comparitor 76, a reference voltage source 78 connected from the output to one input (+) of the comparitor, and a voltage divider 74, 80 connected to the other comparitor input (-). The reference voltage source 78 provides a fixed voltage V_{ref} across it. It may be a small battery or equivalent. The control circuit 75 in the secondary turns ON the MOSFET M2 once it detects a negative voltage at the drain of the MOSFET M2. This reduces the drop across M2. The current decays with constant negative slope in the secondary from time T_1 to time T_2 as it delivers energy to the output. The current eventually crosses zero at time T_2. Then the secondary current 88 reverses, which flows into the drain of the MOSFET M2 producing a positive voltage drop. Where there is a sufficient amount of positive voltage at the drain of the MOSFET M2 detected by the divider formed by the pair of resistors 80 and 74, a control capacitor turns OFF the MOSFET M2 at time T_3. So, at time T_3, the secondary current 88 is negative or "reverse." The reference voltage source 78 is used to regulate the output voltage which modulates the turn OFF time. If the output voltage is low, the MOSFET M2 is turned OFF right at zero current. If the output is higher, then the MOSFET 72 is left ON longer, which pushes more negative or "reverse" current back to the primary circuit. By changing the amount of current going back, the secondary side of the converter can regulate the output. When the MOSFET M2 turns OFF the current that was pushed back (negative secondary current 88), the transformer reverses the primary winding 66. The primary winding starts to move charge out of the MOSFET M1 drain back into the input source 56. This starts to lower the primary drain voltage 84 at time T_3. The resistor 58 provides a delay while this is happening such that the MOSFET M1 turns ON when its drain reaches zero. The greater the current pushed back to the primary from the secondary the faster the drain of the MOSFET M1 will fall. Once M1 is turned on, the whole process repeats. Both MOSFETs M1 and M2 experienced zero voltage turn ON.

Another simple control is illustrated in Fig. 3. All the primary components are the same, but the control of the MOSFET M2 is accomplished with an extra winding

116. The MOSFET M2 itself regulates the voltage by its intrinsic turn-ON threshold. Resistors 112, 114 and the extra winding 116 turns ratio help to adjust the output voltage. The advantage of this topology is that it is very simple. The disadvantage is that the MOSFET M2 is not turned ON very well. But for low power, small converters the topology of Fig. 3 can be very useful.

To illustrate more generally the concept and timing accomplished by the algorithm of the present invention, a more general schematic is shown in Fig. 4A with waveforms in Fig. 4B. The converter can be bi-directional. Assuming that energy is being processed from left to right, a control circuit 202 turns ON a MOSFET M1 at time T_0 (in Fig. 4B). This is a time after it detects a negative or reverse current 222 flowing through the current sensor CS_1 plus a delay so that the drain of the MOSFET M1 has reached zero. It then decides, only when the current 222 has become positive, based on the input voltage or a fixed time, and/or winding voltages, to shut OFF M1. The algorithm on which the control circuit 202 operates turns M1 ON at zero voltage on the drain of M1 and when there is a negative or reverse current 222 in the MOSFET switch M1, and as long as the current is negative the MOSFET M1 must remain ON; then when the current is positive the control circuit 202 is allowed to decide how long to leave the MOSFET M1 ON. The decision on how long to remain ON is based on the input voltage, output voltage, winding voltages or peak current 222. The same algorithm applies to a secondary side control circuit 210. The circuit 210 uses current sensor CS_2. The current in the MOSFET M2 is monitored. M2 is turned ON when its drain is zero and there is a negative current 224 through it. Again the decision to turn OFF is allowed only when the current 224 is positive. The amount of time the current is positive is again up to the power direction and the regulation method used. The way the regulation of the input or the output is accomplished determines the direction of power flow. As long as the base algorithm is followed both switches have zero voltage switching. In Fig. 4B, it can be seen that current through M1 has the same basic shape as current in M2. The waveforms show power flow from primary to secondary since the average of the current 222 in M1 is positive. The gate voltage of M1 and the gate voltage of M2 are primarily inverted except for delays needed to achieve zero voltage switching. At T_0, M1 is turned ON, at T_1, the current 222 crosses zero, and after that the control circuit 202 decides when to turn OFF M1. At T2, the control circuit 202

turns OFF M1 with a low gate voltage 226. After a short delay, to wait for zero volts on the drain of M2, M2 is turned ON by the control circuit 210 applying to the gate of M2 the voltage 228 since it detected a negative current through CS_2. At time T_3, the current 224 crosses zero and again the decision to turn OFF is allowed only when the current 224 is positive. At time T_4, the secondary control circuit 210 decides to shut OFF based on one or more of the input voltage 200, output voltage 212, winding voltage 208, or current level in CS_2.

The foregoing descriptions of preferred embodiments are exemplary and not intended to limit the claimed invention. Obvious modifications that do not depart from the spirit and scope of the invention as claimed will be apparent to those skilled in the art. For example, although MOSFETs are described as the primary switch and secondary synchronous rectifier or switch, other semiconductor switches may be employed.